JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 38, No. 6, November–December 2001

Hyper-X Aerodynamics: The X-43A Airframe-Integrated Scramjet Propulsion Flight-Test Experiments

IN 1996 NASA initiated the Hyper-X program as part of an initiative to mature the technologies associated with hypersonic airbreathing propulsion. The primary goals of the Hyper-X program are to demonstrate and validate the technologies, the experimental techniques, and the computational methods and tools required to design and develop hypersonic aircraft with airframe-integrated, dual-mode scramjet propulsion systems. Hypersonic airbreathing propulsion systems, studied in the laboratory environment for over 40 years, have never been flight tested on a complete airframe-integrated vehicle configuration. This series of papers outlines the ground-based aerodynamic analysis efforts, including the experimental wind-tunnel test programs and the computationally based design and assessment activities, which led to the first Hyper-X X-43A vehicle flight test. Six of the seven papers in this series were first presented in a special invited papers session at the 18th AIAA Applied Aerodynamics Conference held in August 2000. The seventh paper, which has a more obvious scramjet propulsion test program emphasis, was presented at the 10th AIAA International Space Planes Conference held in April 2001. It is included here as a means by which to highlight the aeropropulsive interactions and coupling for this particular class of vehicle with an airframe-integrated scramjet propulsion system. Collectively, these papers provide a very brief overview of the broad effort executed to define and develop the aerodynamic databases in support of the flight-test element of the Hyper-X program. They offer insights into the aerodynamics-related engineering challenges directly associated with the X-43A Research Vehicle flight test, as well as documenting several of the key advances made to the state of the art in ground-based airframe-integrated scramjet propulsion system testing and analysis and in the area of hypersonic boundary-layer trip design.

Although the first flight-test attempt, conducted in June 2001, ended prematurely in a failure during the rocket-assisted boost to the scramjet test condition, two additional expendable X-43A vehicles are currently being readied for flight tests. The eventual successful flight testing of these vehicles will provide a unique opportunity to obtain hypersonic aerodynamic data on a slender-body, nonaxisymmetric airframe with an airframe-integrated scramjet propulsion system. Because of the highly integrated nature of the propulsion system with the airframe, the traditional distinctions between vehicle aerodynamics and propulsion are blurred. Therefore in addition to the scramjet operational and performance data that will be obtained, a tremendous amount of aerodynamic data will be gathered during the flight tests, so that a more complete understanding of the aeropropulsive interactions in flight can be formulated.

The first in this series of seven papers provides a general overview of the Hyper-X program and the flight-test mission sequence. The emphasis here is on the overall aerodynamic database development activities in support of the Hyper-X X-43A flight-test program. A summary is provided of the overall ground-based wind-tunnel test program and parallel computational fluid dynamics (CFD) analysis efforts conducted to support the entire X-43A flight-test mission profile. This is followed by some specific details on the X-43A Research Vehicle's aerodynamic characteristics, including the direct and indirect effects of the airframe-integrated scramjet propulsion system operation on the basic airframe stability and control characteristics. More specific details on all of the subject areas are provided in the following papers.

The second and third papers focus specifically on the aerodynamics associated with the stage separation event. Although the ultimate goal of the flight test is to obtain data at and around the hypersonic scramjet test conditions, delivering the X-43A Research Vehicle to the test point presents a number of unique challenges. By far the highest-risk element of the mission was deemed to be the stage separation event, in which the X-43A Research Vehicle must separate from the first-stage rocket booster at the extreme environmental conditions associated with flight at Mach seven and dynamic pressure in excess of 1000 lb/ft^2. To reduce the risk associated with the stage separation event, a comprehensive wind-tunnel test program and computational effort using state-of-the art CFD codes and capabilities was undertaken. The second paper describes in detail the stage separation wind-tunnel test program and offers some insight into the complexities of testing two nonaxisymmetric bodies in close proximity. The third paper provides details of the stage separation computational activities, which included benchmarking of codes with experimental data and extending the aerodynamic database with solutions when experimental methods could not provide results or sufficient detail. The computational activities also helped to provide a more thorough and detailed understanding of the complex flow structure between the two bodies throughout the separation event.

The comprehensive series of wind-tunnel tests on the X-43A Research Vehicle configuration are described in detail in the fourth paper. These tests provided airframe aerodynamic performance and stability and control data covering the entire flight-test envelope from the hypersonic test conditions at and around the scramjet test point through the supersonic, transonic, and subsonic regimes the X-43A must fly through before completing the flight-test mission. Brief descriptions of the various wind-tunnel facilities, wind-tunnel test models, and test techniques and rationale are provided, followed by select sample data from several of the tests conducted.

The fifth paper provides detail on the computational aspects of the coupled aeropropulsive performance prediction methodologies employed during the preflight program. The highly integrated nature of this scramjet flowpath within the configuration airframe presents distinct challenges to the aerodynamicist: How to separate and properly account for the scramjet-propulsion-induced effects on airframe aerodynamics and overall performance? In this paper a description is provided of the computational analysis tools and methodologies that were utilized to develop the preflight predictions of the powered aeropropulsive flight characteristics. A brief examination of the detailed computational predictions of the flowfield structure during the scramjet operation is provided, followed by some thoughts on future computational technology development requirements for hypersonic propulsion-airframe integration analysis.

The sixth paper in this series provides the logical link between the scramjet propulsion test and analysis activities and the overall vehicle aerodynamics and performance database development. A series of powered airframe-integrated scramjet tests were conducted in the NASA Langley 8-Foot High Temperature Tunnel using a full-scale airframe structure that duplicated the entire X-43A three-dimensional propulsion flowpath surface and utilized an exact duplicate of the flight engine. These tests replicated the Mach number and enthalpy conditions expected at the design flight-test point. This test series provided engine performance and operability data and the final ground-based design and database verification benchmarks for the X-43A Mach seven flight tests. Details are provided on the test series objectives, the facility and test article hardware, and results from the test, which helped to tie all of the aerodynamic and propulsion performance analysis predictions together, prior to obtaining the ultimate benchmark set of data from flight tests.

The seventh and final paper deals specifically with the hypersonic boundary-layer trip design and development activity, which was integral to maximizing the scramjet propulsion system designed performance. To ensure robust scramjet engine operation, the boundary layer entering the engine inlet must be turbulent to minimize the possibility of separated flow conditions and inlet flow distortion. Ingestion of a turbulent boundary layer increases inlet operability and enhances overall scramjet engine performance. Criteria for natural boundary-layer transition indicate that some sort of artificial tripping mechanism must be employed on the X-43A Research Vehicle forebody to ensure turbulent flow conditions at the inlet for the Mach seven scramjet test conditions. A program was undertaken to develop and tailor a hypersonic boundary-layer trip design that would ensure turbulent flow at the scramjet inlet to maximize engine performance while at the same time minimizing aerodynamic performance losses resulting from the induced drag on the vehicle. Various trip designs were investigated and tested in a number of hypersonic facilities. The overall hypersonic boundary-layer trip development test program and selection criteria are described, and details of experimental results are provided.

Even at this point in the Hyper-X program, prior to the first successful flight test, a tremendous amount of knowledge has been gained through ground test and computational analysis efforts regarding scramjet propulsion system and airframe aerodynamic interactions. Several hypersonic airbreathing propulsion follow-on program studies are currently underway and are utilizing the wealth of knowledge and lessons learned in the ground-based testing and computational analysis portions of the Hyper-X program. The Hyper-X program remains strong and is committed to meeting its stated goals through eventual successful flight tests of the second and third X-43A vehicles.

Walter C. Engelund
NASA Langley Research Center